

# The Minimally Invasive Repair of Pectus Excavatum

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Only patients with a severe pectus excavatum deformity should be candidates for surgical repair. Mild and moderate degrees of deformity should be treated with a deep breathing and exercise program and the vacuum bell. The best age for repair is during puberty, but successful repair in adult patients (up to 70 years of age) has been reported. Those scheduled for minimally invasive repair should be measured for bar length and screened for metal allergies. The minimally invasive technique for pectus excavatum repair is done thoracoscopically and requires no rib cartilage or sternal resection. Instead, it relies on bracing the anterior chest wall with a sub-sternal support bar placed in position under the sternum after first correcting the deformity with an introducer specially developed for the procedure. Two bars generally give better correction than one bar. It is essential that the bars be adequately stabilized to prevent bar displacement and recurrence of the deformity. Several techniques have been developed to elevate the sternum during mediastinal tunneling to improve thoracoscopic visibility in very severe and asymmetric deformities. Since 1987 we have evaluated 3836 patients in our chest wall deformities clinic, of whom 1921(50%) have undergone repair. 1738 patients were primary repairs and 1346 of these have had their bars removed two to three years after placement. The biggest challenge in the early years was bar displacement but that has now been reduced to just over 1% by use of a stabilizer on the left side and "0" PDS pericostal sutures on the right side. 88.9% of patients reported an excellent result, 9.6% a good result and 1.5% a poor or failed result. In conclusion: The minimally invasive repair of pectus excavatum is highly successful when carried out by experienced surgeons in a center dedicated to the management of chest wall malformations. Operative Techniques in Thoracic and Cardiovascular Surgery 19:324-347 © 2014 Elsevier Inc. All rights reserved.

**KEYWORDS** Pectus excavatum repair, minimally invasive

## Introduction

The minimally invasive repair of pectus excavatum uses sternal bracing to correct the deformity and requires no costal cartilage or sternal resection. It was introduced in 1987, at a time when most centers advocated wide resection of the anterior chest wall structures in very young patients (before school age).<sup>1,2</sup> As a result of the wide resection, these young patients developed a very rigid anterior chest wall, and in some instances, interference with the growth centers would lead to asphyxiating chondrodystrophy.<sup>3,4</sup> The minimally invasive procedure was therefore initially developed

for prepubertal patients who have a soft and malleable chest to avoid these complications. During the 25 years since the introduction of the minimally invasive procedure, experience with older patients has shown that adult patients still have significant residual flexibility of the anterior chest wall, and as a result, an increasing number of centers have published reports of successful repair in adults up to 70 years of age.<sup>5,6</sup>

There are several advantages of the minimally invasive procedure. The most important is the fact that the chest wall maintains its normal function and flexibility after repair, as no tissues are resected. Multiple studies performed after repair and bar removal have confirmed significant improvement in cardiopulmonary function in these patients.<sup>7-9</sup> Other advantages include a completely normal appearance of the chest postoperatively with a "good" or "excellent" outcome reported in 98% of primary repair patients,<sup>10</sup> a relatively short operating time (usually less than 1 hour), and minimal blood loss ( $\pm 10$  ml). Body image studies have shown dramatic improvement.<sup>11</sup> As with all operations, attention to detail is vitally important for a successful outcome and avoiding complications. The procedure should only be done by surgeons who have been adequately trained (Figs. 1-14).<sup>10</sup>

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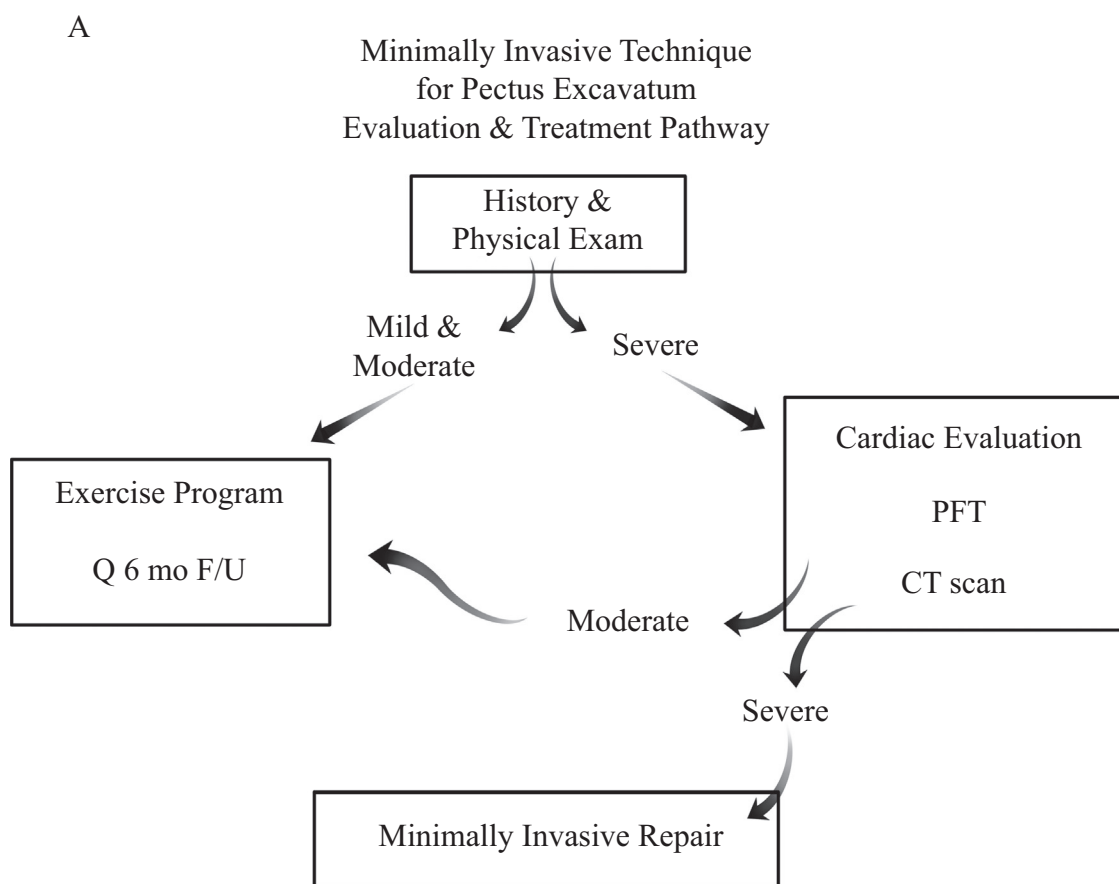
Dr. Nuss reports receiving consulting and lecture fees from Biomet Microfixation and has a patent on the pectus bar that expires in 2017. Dr. Kelly reports receiving consulting and lecture fees from Biomet Microfixation.

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## Indications



**Figure 1** (A) Only patients who have a severe deformity should be considered candidates for surgical pectus excavatum repair. Patients with mild or moderate deformity should be treated conservatively with an exercise and posture program and the vacuum bell.<sup>12</sup> Our criteria for operation are that patients should exhibit at least 2 of the following criteria to be considered candidates for surgical correction: (1) symptoms of dyspnea on exertion, lack of endurance, or chest pain; (2) documented progression of the deformity; (3) a severe deformity on examination with clinical evidence of cardiac compression or pulmonary compression or both; (4) CT or MRI scan of the chest confirming cardiac and pulmonary compression or displacement and a pectus index above 3.25; (5) pulmonary function studies showing a restrictive pattern; (6) echocardiogram and EKG showing significant abnormality such as cardiac compression, mitral valve prolapse, left axis deviation, RBBB, or arrhythmia; and (7) severe body image disturbance with depression, asocial behavior, or suicidal thoughts. PFT = pulmonary function testing; F/U = follow up; CT = computed tomography; MRI = magnetic resonance imaging; EKG = electrocardiogram; RBBB = right bundle branch block.

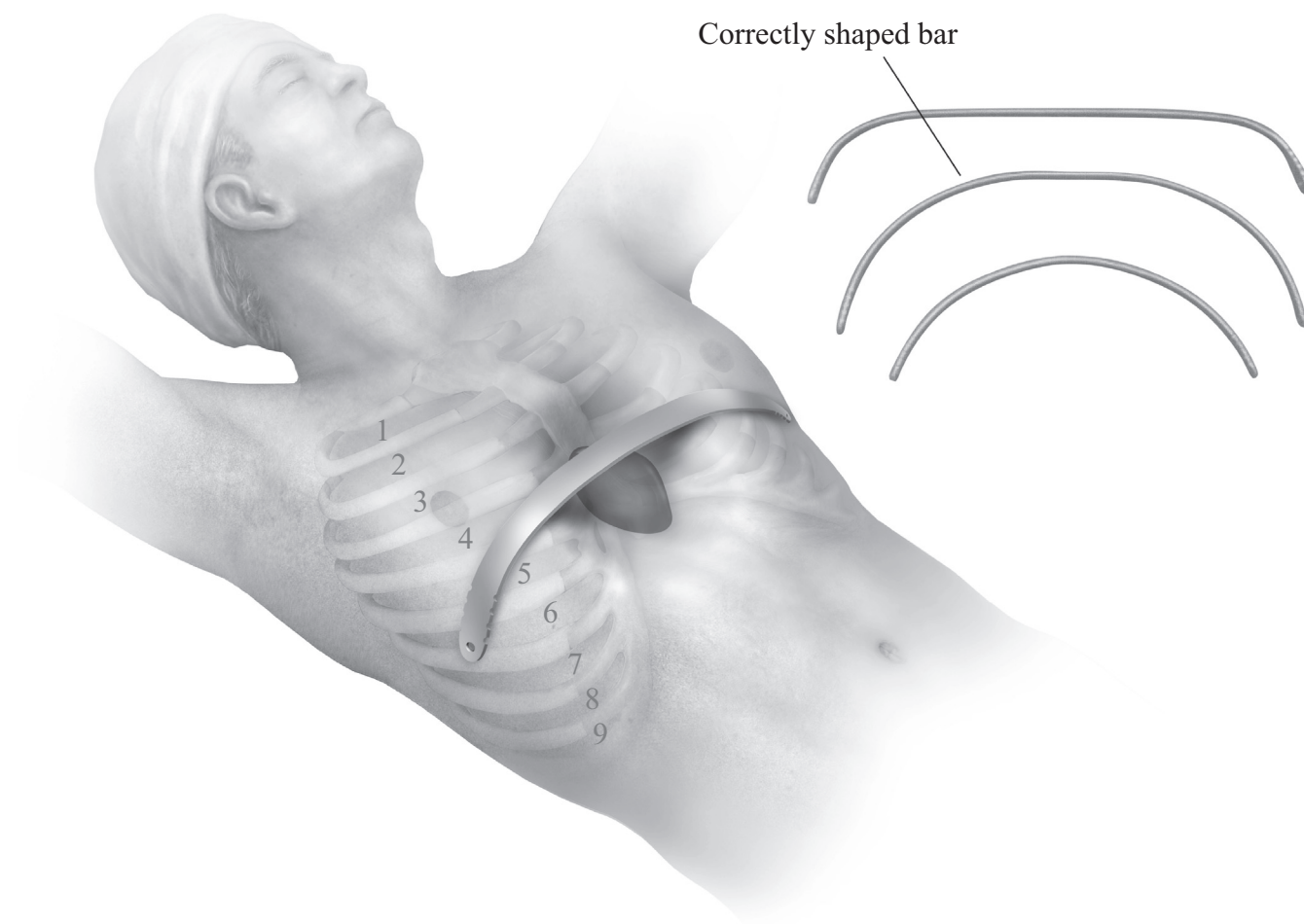
## Measuring the Patient to Determine Bar Length

B



**Figure 1** (Continued) (B) To determine the correct length of the pectus substernal bar, the patient is measured from the right to the left midaxillary line and then 2 cm (or 1 in) are subtracted from that measurement as the bar takes a shorter course inside the chest than the tape measure does on the outside of the chest. The patient should initially be measured in the clinic so that the correct length bar can be ordered in time for the surgical repair. At this time, the patient should also be questioned and checked for potential metal allergies, especially allergy to nickel, which is a component of surgical steel. If there is a suspicion of nickel or other metallic allergies, then a titanium bar should be ordered. Presently, we perform formal patch testing for all components of the surgical steel bar (Ni, Cu, Co, Cr, Mn, and Mo).<sup>13</sup> The measurement for bar length should be rechecked immediately before surgery to ensure that the previous measurement still applies, especially if there has been a time lapse between the clinic visit and the date of surgery, and that the bar that was ordered is the correct one.

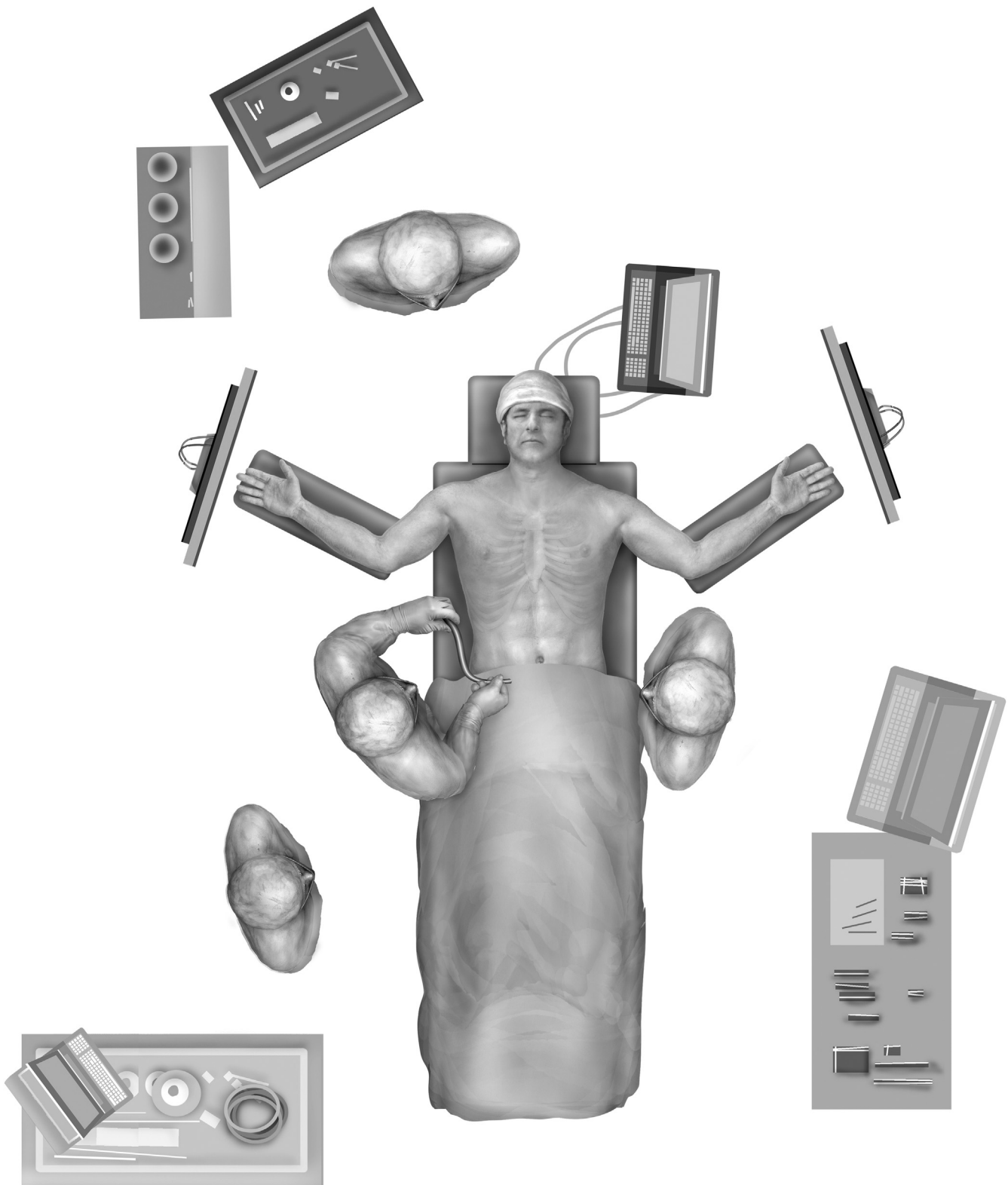
## Correct Bar Configuration



**Figure 2** Correct configuration is very important as the chest should be slightly overcorrected at the end of the procedure. The bar should have a convex, semicircular shape except for a 2-4 cm flat section in the middle to support the sternum. The bar should be symmetric. Park and others have advocated bending the bar asymmetrically for asymmetric deformities, but we have not found that to be advantageous or necessary.<sup>14</sup> If the bar is too flat (table-top configuration), it will undercorrect the deformity, which may predispose to recurrence. In addition, if the bar is too flat, it is possible for the lung to herniate between the bar and the anterior chest wall. On the contrary, if the bar is bent too much, it will be unstable and cause overcorrection. It is often necessary to remold the bar after initial insertion and rotation.

The bar can be prebent to a satisfactory shape by the manufacturer (BiometMicrofixation, Jacksonville, FL) using computer-assisted design or computer-assisted manufacturing techniques. When requesting a prebent bar, the surgeon must indicate the location of bar placement on the patient's CT or MRI and specify the bar length. CT = computed tomography; MRI = magnetic resonance imaging.

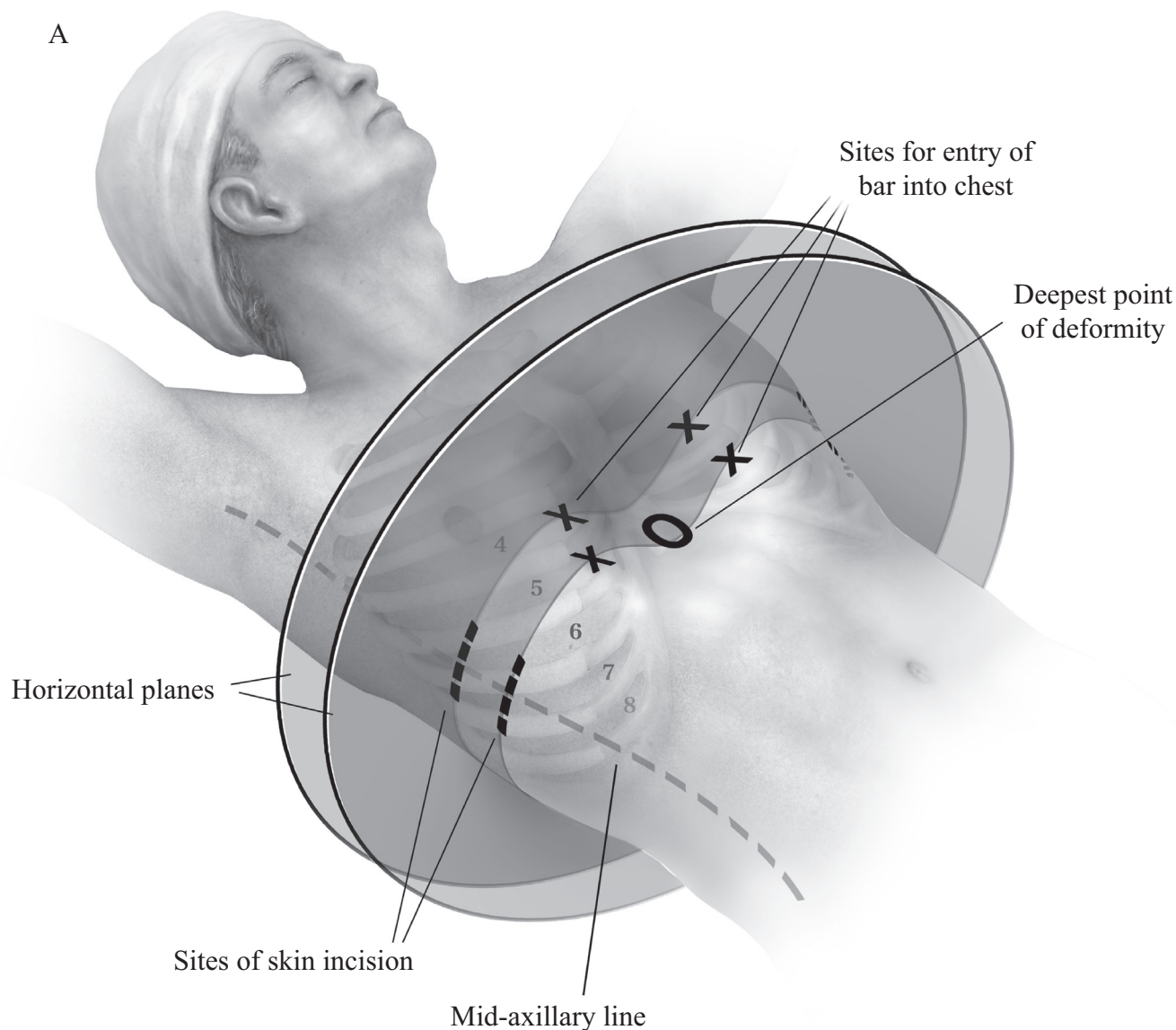
## Positioning The Patient



**Figure 3** All our patients have their blood typed and screened in case there is an urgent need for transfusion. A thoracotomy and a median sternotomy tray should be readily available in the operating room, but unopened. After induction and intubation, the patient should be positioned with both arms abducted approximately  $70^\circ$  from the chest wall. This degree of abduction allows good access to the lower chest wall and does not cause brachial plexus injury. The elbows should be slightly flexed. The wrists may need to be elevated on foam to allow a relaxed arm. The surgical site should be well prepared with antiseptic solution and IV antibiotics administered to minimize the risk of subsequent bar infection. The antibiotics should be continued for 48 hours or until the temperature is back to normal and the patient is using his incentive spirometer without difficulty. A preoperative pain protocol should be part of the total pain management program.

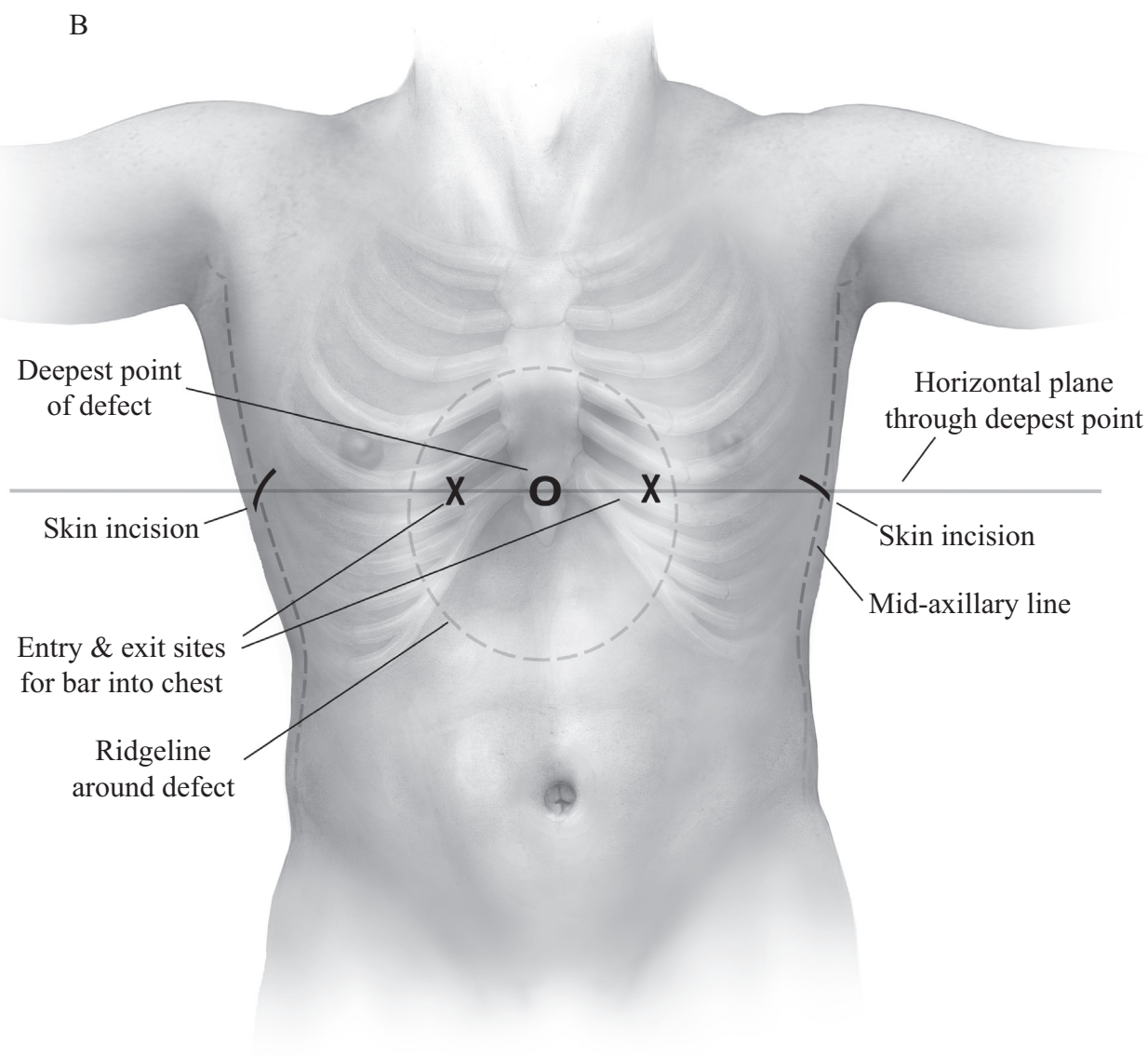


## Marking the Anterior Chest Wall

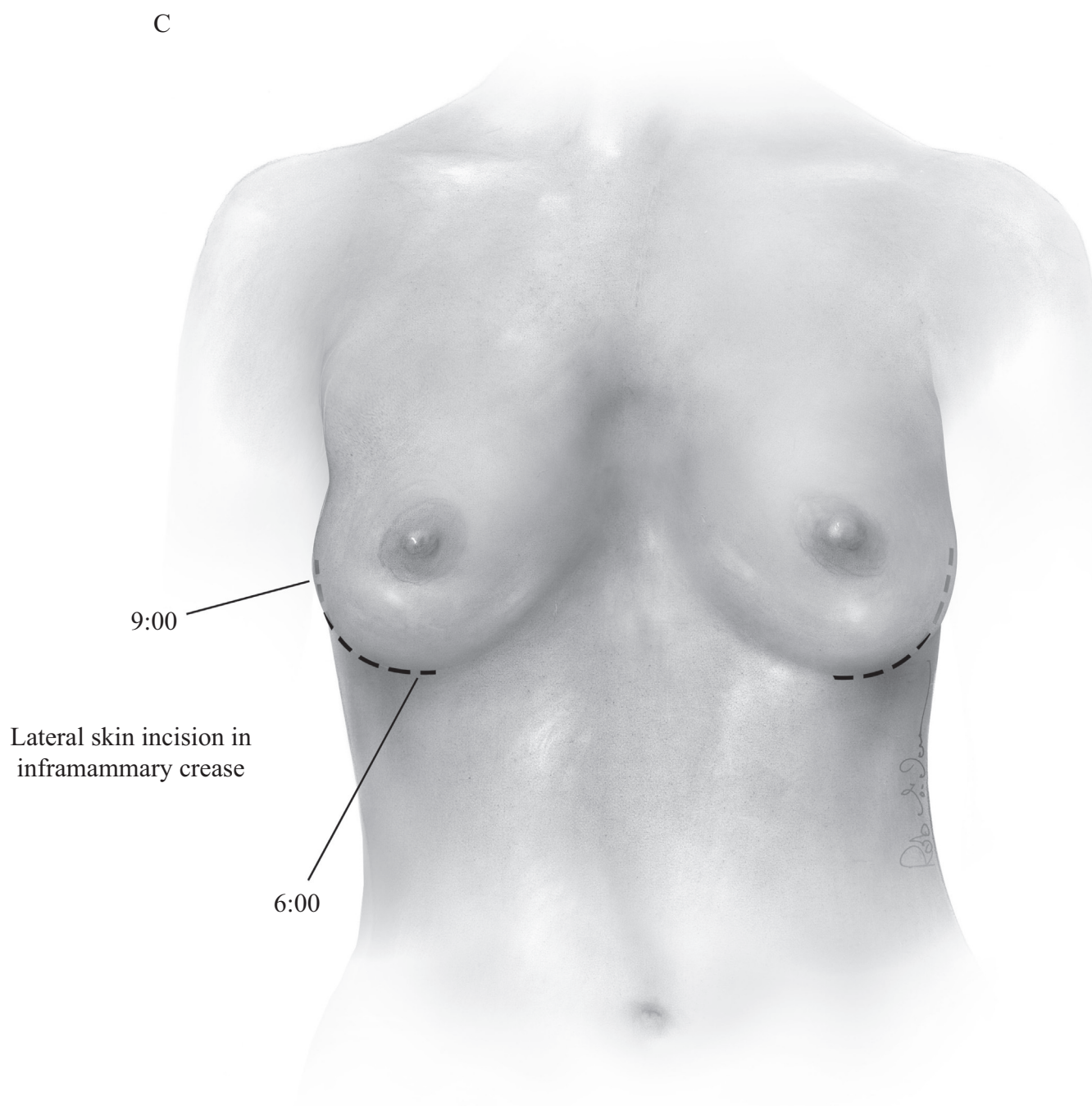


**Figure 4** (A) Selecting the surgical site for bar insertion is vitally important. To achieve an excellent result, the bar should be under the deepest point of the depression. However, if the deepest point of the depression is below or inferior to the sternum, then 2 bars need to be placed—one under the deepest point of the depression and the other one under the lower sternum. If only one bar is used and it is placed inferior to the sternum, it will not correct the deformity, as only the soft tissues will be elevated. It is therefore crucial to always elevate the sternum with at least 1 bar.

Usually 2 bars give better correction than 1 bar and should always be considered in older patients, asymmetric patients, wide deformities, and severe deformities. Our overall frequency of using 2 bars has increased from 12% in 2000 to 38% in 2013, and in the aforementioned categories of pectus excavatum, it is more than 50%.



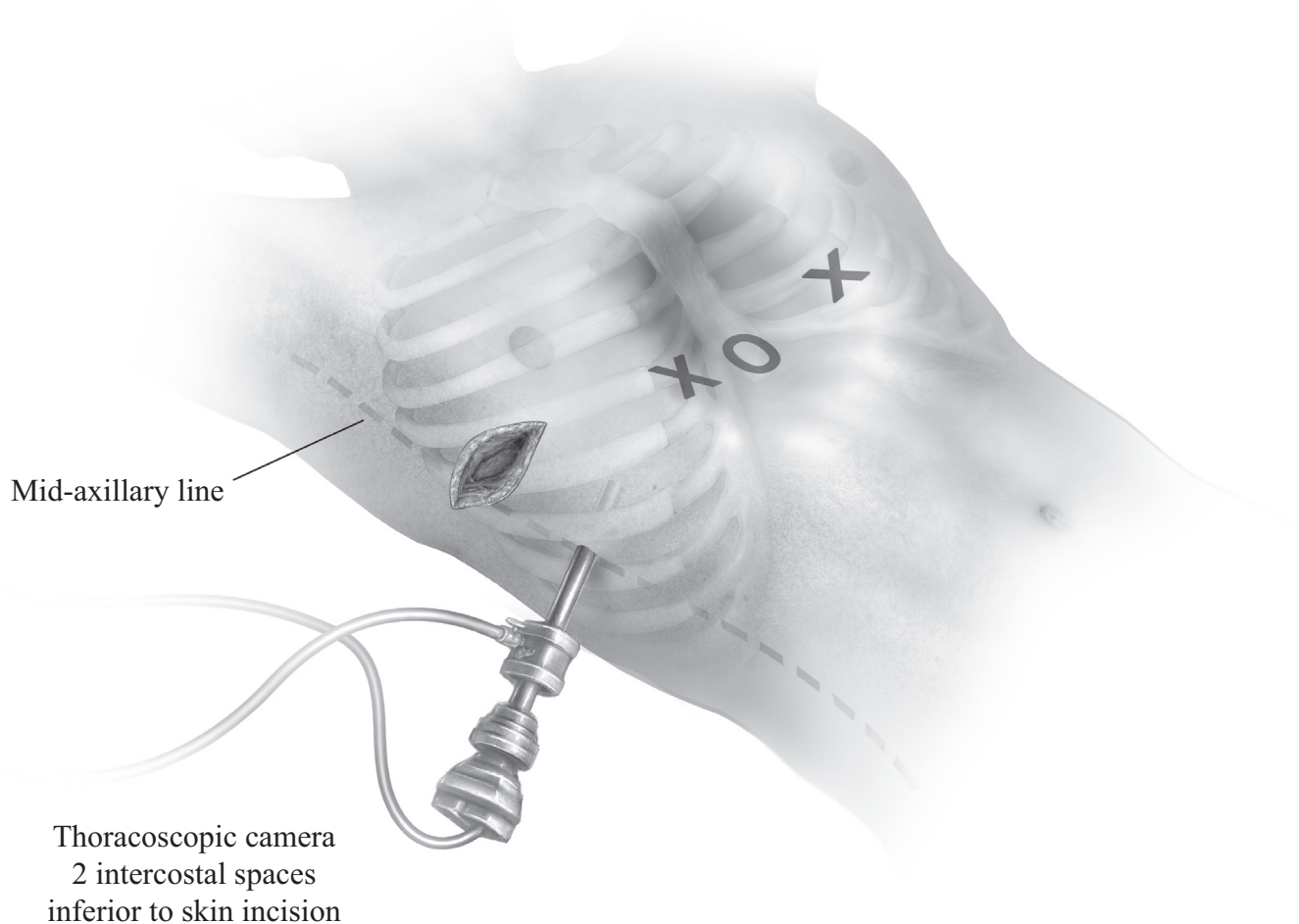
**Figure 4** (Continued) (B) To correctly mark the patient, a marking pen is used, and a small circle is drawn over the deepest point of the depression. The right and left intercostal spaces that are in the same horizontal plane as the deepest point of the depression are then marked out. An "X" is drawn in each of these intercostal spaces at the point just medial to the point where the anterior chest wall starts to cave in. The "X" marks the point where the pectus bar enters the chest on the right and exits the chest on the left. Following the same horizontal plane laterally, 2 horizontal lines are drawn between the mid-axillary and anterior-axillary lines to demarcate the skin incision sites on each side of the chest.



**Figure 4** (Continued) (C) In mature female patients, an alternative incision is used. Instead of a lateral thoracic incision, the incision is placed in the inframammary crease and runs from the 6-o'clock to the 9-o'clock position. If necessary, it can be extended laterally from the 9-o'clock position, but this is not usually necessary.

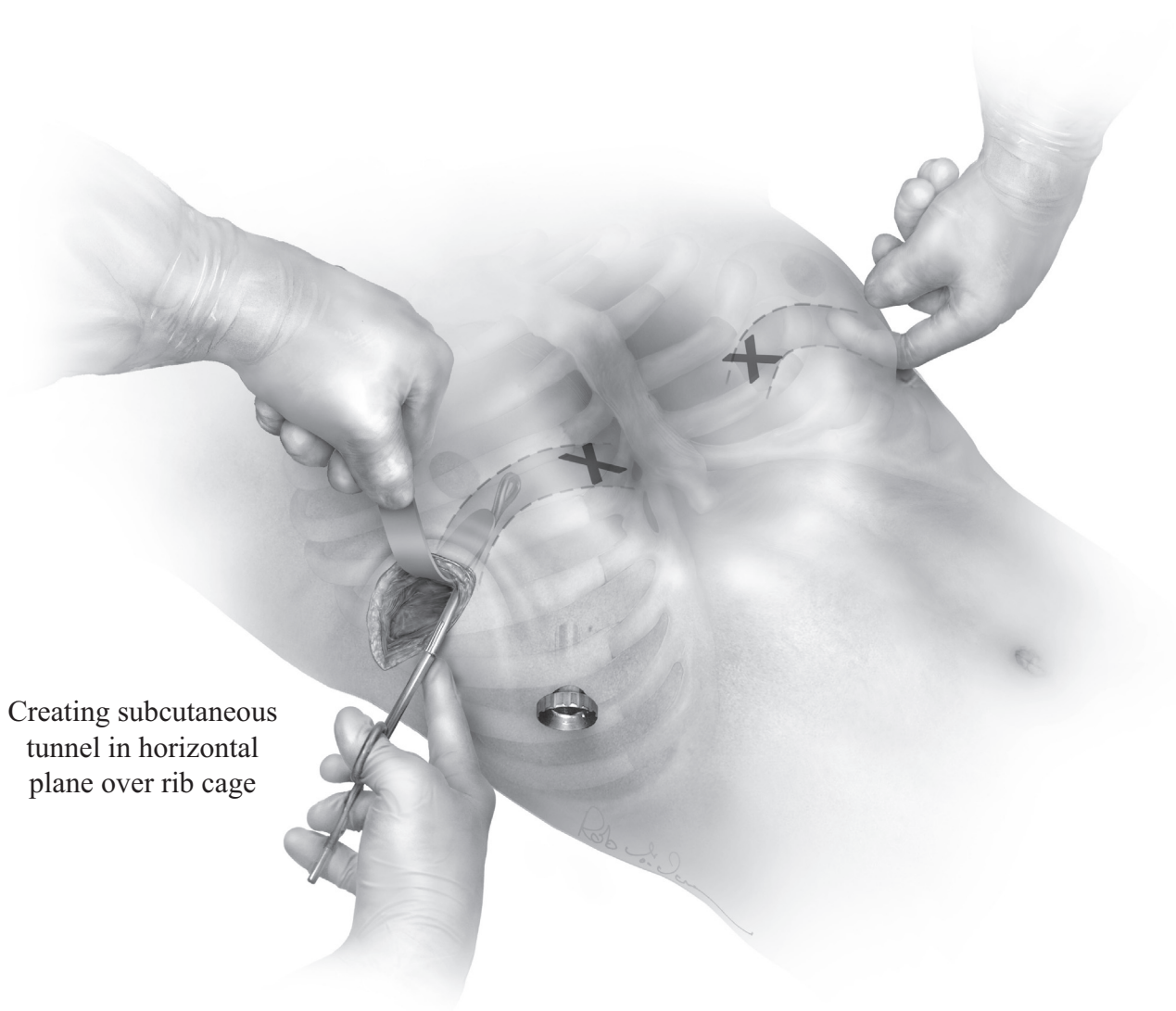


## Thoracoscopy



**Figure 5** Thoracoscopy is essential for both safety and confirming correct bar placement. The scope may be inserted on the right side, left side, or both sides. Most surgeons prefer starting on the right side and proceeding to the left as necessary. The 5-mm trocar is inserted into the right lateral chest in the midclavicular line, approximately 2 intercostal spaces inferior to the proposed incision site. When inserting the trocar, it needs to be directed superiorly to avoid injuring the diaphragm and liver. Visibility is improved by using either CO<sub>2</sub> insufflation up to 5-mm Hg pressure or by using single-lung ventilation. The CO<sub>2</sub> insufflation pressure minimizes capillary bleeding by raising intrathoracic pressure above capillary pressure. A thorough inspection of the right chest is carried out with the thoracoscope before making the skin incisions to check that there is no unexpected pathology present and secondly to confirm that the internal anatomy corresponds with the external markings and proposed incision sites. External pressure applied to the “X” over the right intercostal space, when viewed from inside the chest, will show whether the entry site is in line with the deepest point of the depression internally. The thoracoscope may be removed while the subcutaneous tunnel is being created. The position of the internal mammary vessels is noted to avoid injuring them. Many surgeons find that a 30°-angled or flexible-tip scope facilitates visualization during the mediastinal dissection under the deformity.

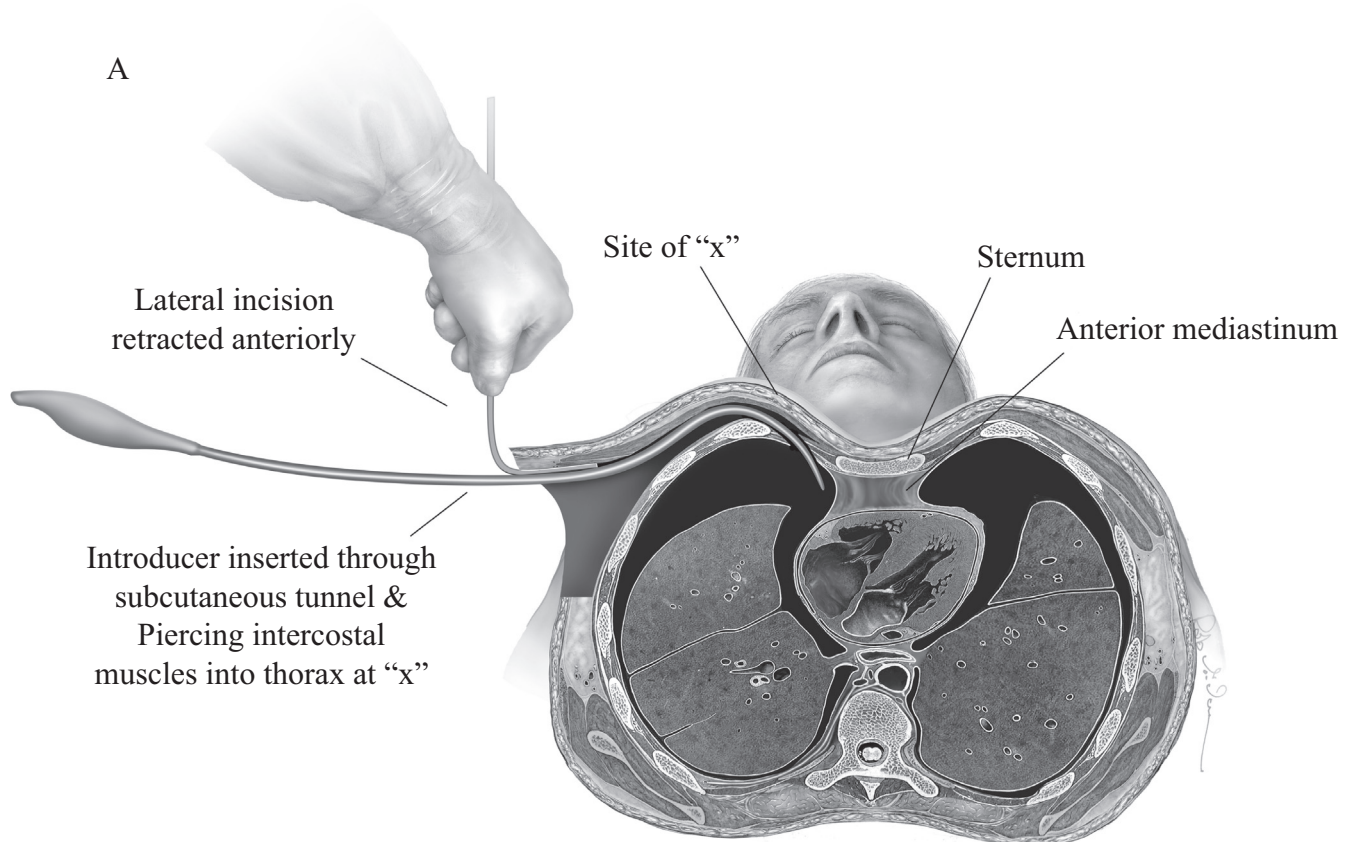
## Creating the Subcutaneous Tunnel



**Figure 6** Bilateral, horizontal lateral thoracic skin incisions are made from the anterior-axillary to the midaxillary lines and carried down through the subcutaneous tissues onto the surface of the rib cage. A subcutaneous tunnel is then created from the incision site up to the "X" marked on the anterior chest wall. The "X" should be just inside or "medial to the point where the deformity starts to cave inward." If the tunnel is superior to the origin of the pectoralis muscles, then the tunnel should proceed under the pectoralis muscles. In mature female patients, the inframammary crease incision is used instead.

We generally do not place bars superior to the fourth intercostal space to avoid sternoclavicular dislocation and to keep the bar out of the axilla.

## Creating the Substernal Tunnel



**Figure 7** The thoracoscope is reinserted into the right chest and directed to the anterior chest wall. A retractor is inserted into the subcutaneous tunnel, and the tunnel elevated in an antero-medial direction. A tonsil vascular clamp is advanced into the subcutaneous tunnel up to the "X" where it is used to create a thoracostomy opening between the ribs at the point marked with an "X." The tonsil clamp is withdrawn, and the appropriate size introducer is inserted into the subcutaneous tunnel with the tip facing posteriorly. The introducer is advanced into the tunnel until it is at the point marked "X." The tip of the introducer is gently pushed through the newly created thoracostomy under thoracoscopic guidance taking care to avoid injury to the underlying structures. Once the introducer has entered the chest cavity, it is turned over so that the tip faces anteriorly. From this point onward, the tip should be kept under constant view through the thoracoscope.

The introducer is slowly advanced to the mediastinum, and then by first using an anterior to posterior or "pawing" motion, the pleura and pericardium are carefully peeled off the under surface of the sternum. When a tissue plane has been established and the foamy mediastinal tissue is visualized, then the introducer may also be moved in a side to side or superior to inferior motion thereby enlarging the tunnel. *At no time should this tunneling procedure be done as a blind technique.* The EKG monitor should be audible to both the surgical and anesthetic staff to immediately recognize arrhythmia. As the careful dissection continues, the introducer is slowly advanced across the mediastinum and then pushed through the corresponding intercostal space on the left side at the point marked with an "X," and then advanced out through the left subcutaneous tunnel. The pericardium and substernal tunnel are carefully inspected before proceeding to the next step. EKG = electrocardiogram.

When the tip of the introducer has emerged through the X in the intercostal muscles on the left side, it is advisable to attach a bone hook, wire suture, or towel clamp to the hole in the end of the introducer and have the assistant pull in a vertical or anterior direction while the surgeon applies transverse pressure, which prevents stripping the intercostal muscles on the left side.

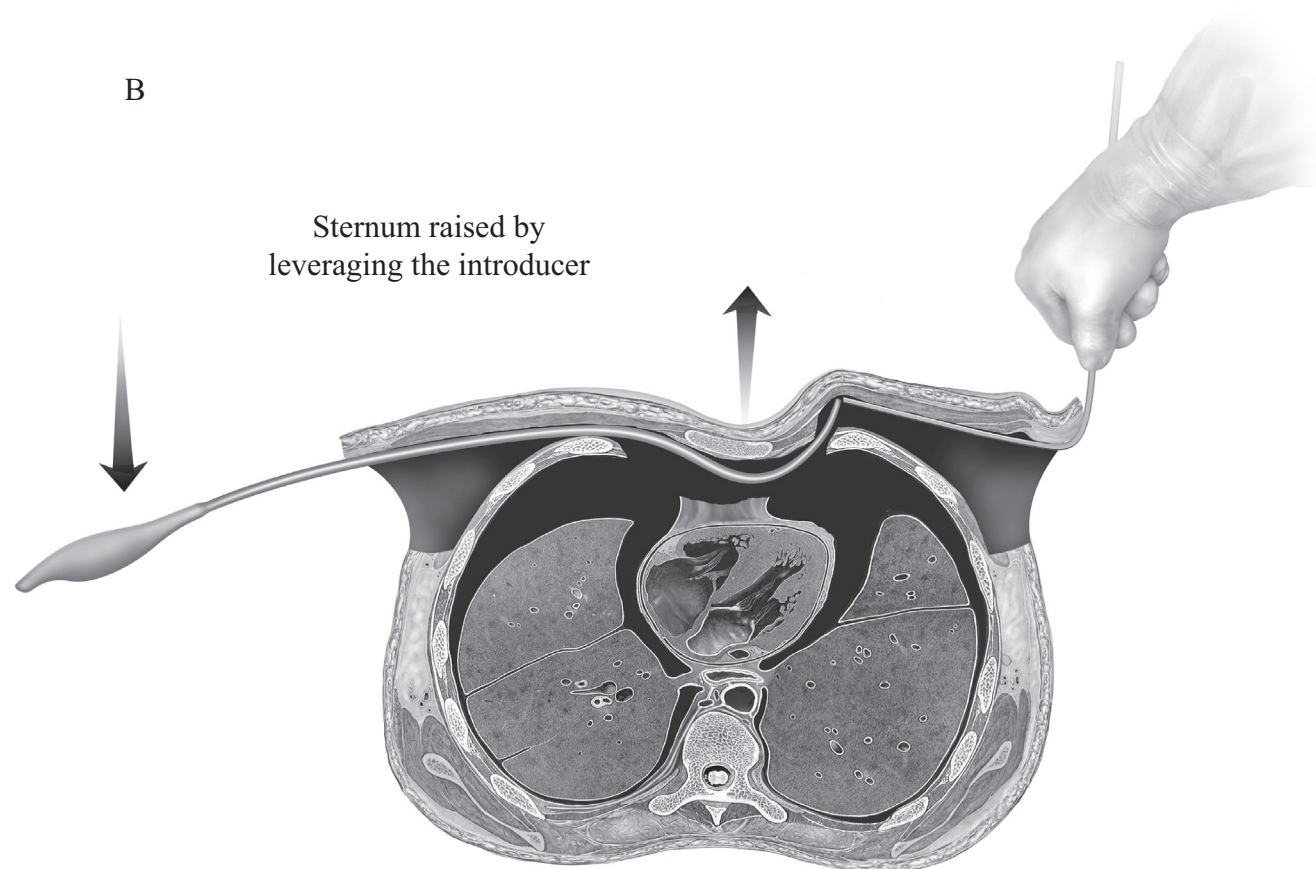
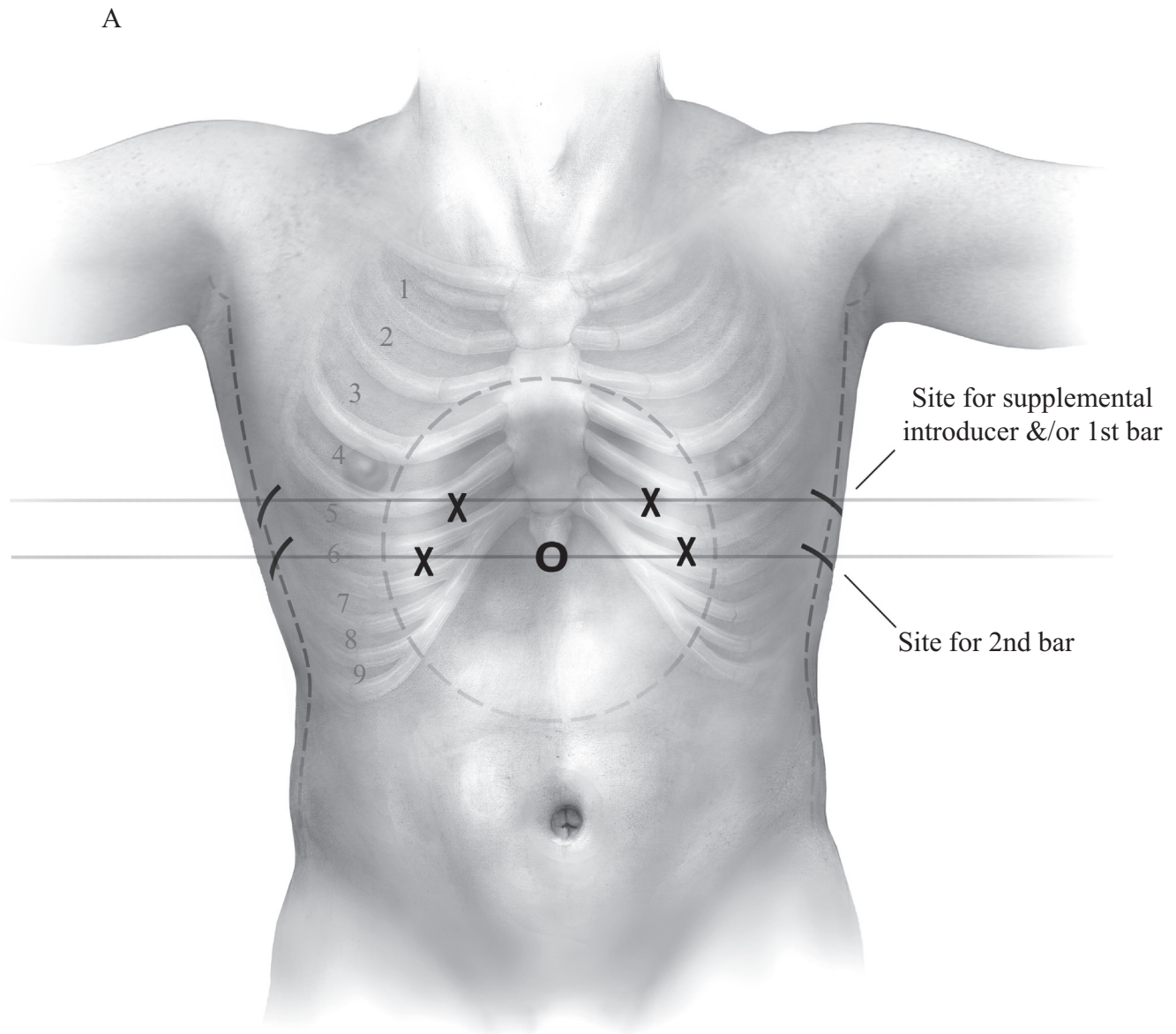


Figure 7 (Continued)

## Special Techniques for Complex Cases

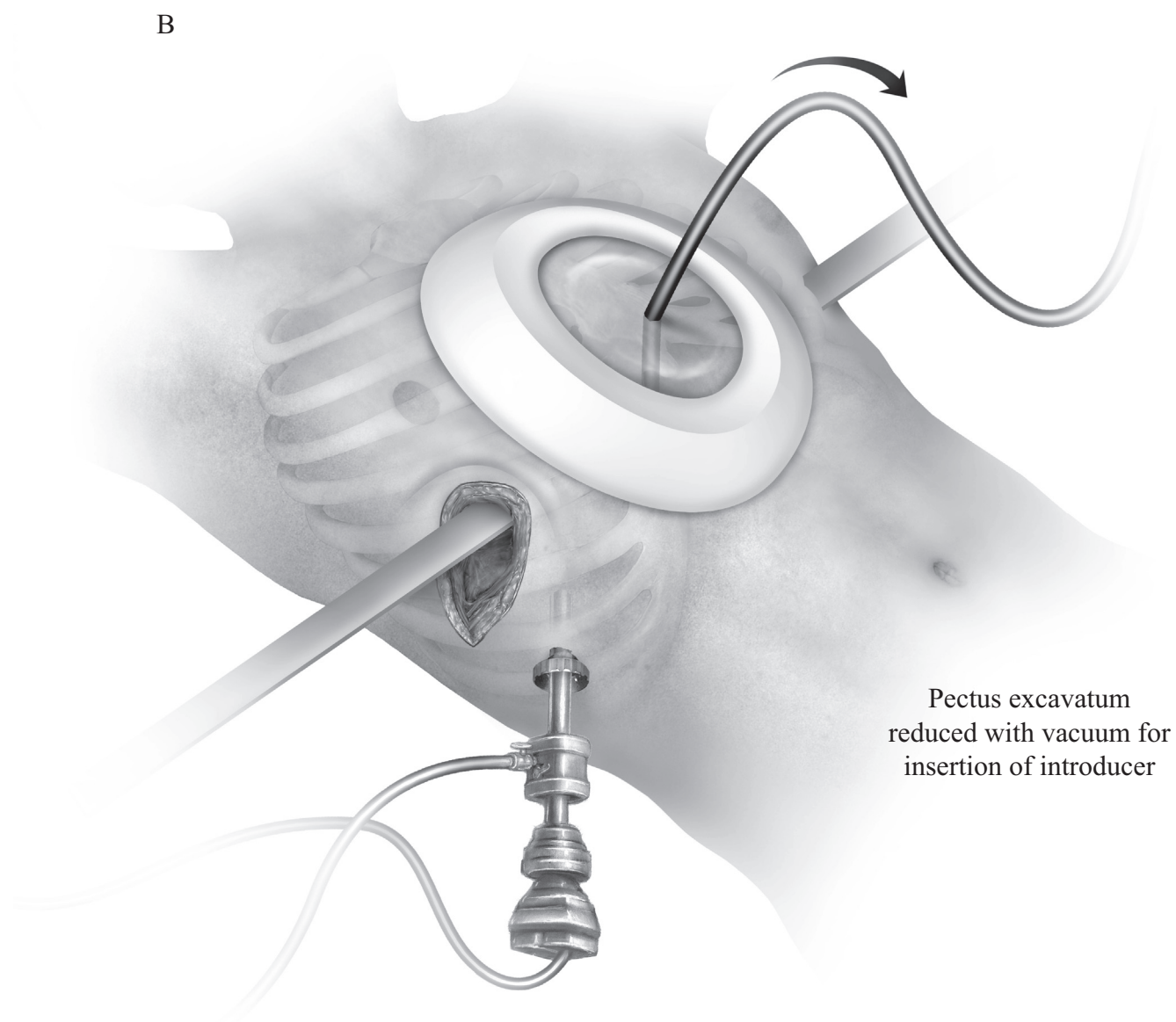


**Figure 8** Sternal elevation by one of the several techniques makes the operation easier and safer. In some cases, the deformity is so severe and complex that it is not possible to see the tip of the introducer beyond the first 1-2 cm. In these patients, it is necessary to elevate the sternum before starting to tunnel under the deepest point of the deformity.

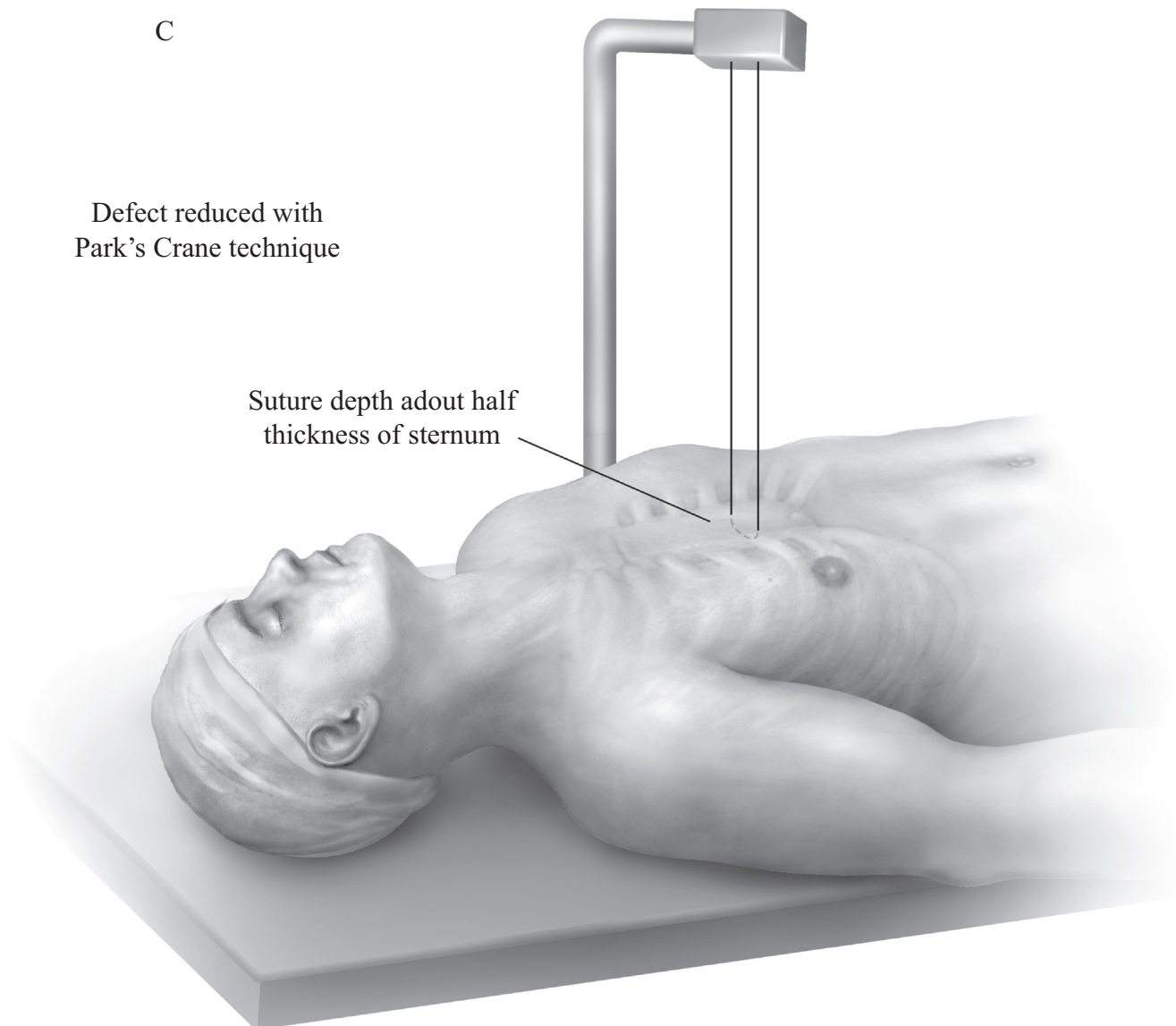
(A) One technique to accomplish this is to use multiple bars. First, create a tunnel and pass an introducer 1 or 2 intercostal spaces superior to the deepest point.

By leaving this introducer in place, the sternum may be sufficiently elevated to allow access to the deepest point without the risk of cardiac or pulmonary injury.





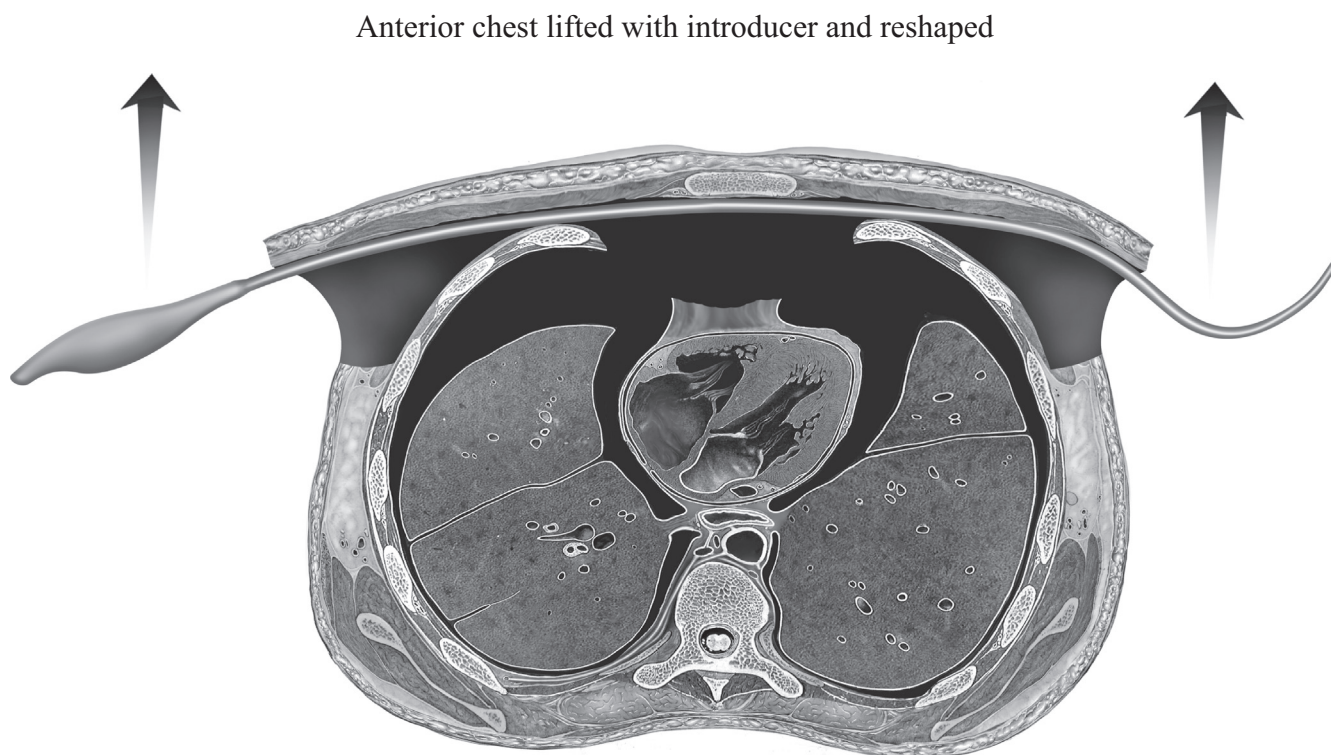
**Figure 8** (Continued) (B) A second technique to elevate the sternum before substernal dissection is to use the “vacuum bell” developed by Max Klobe,<sup>12</sup> which will usually elevate the sternum from 1-2 cm, which may be sufficient to allow a safe dissection to occur.



**Figure 8** (Continued) (C) A third technique is to use Park's Crane technique,<sup>14</sup> whereby 1 or 2 wire sutures are passed through the anterior plate of the sternum and attached to a Rultract Retractor, which can winch the sternum up into the desired position.

Other techniques include making an infrasternal incision and inserting a long retractor and elevating the sternum manually or inserting a Volkmann bone hook through a small incision immediately lateral to the body of the sternum and then the sternum is lifted manually as described by Uemura et al.<sup>15</sup> and Rygl et al.<sup>16</sup>

## Elevating the Sternum and Correcting the Deformity



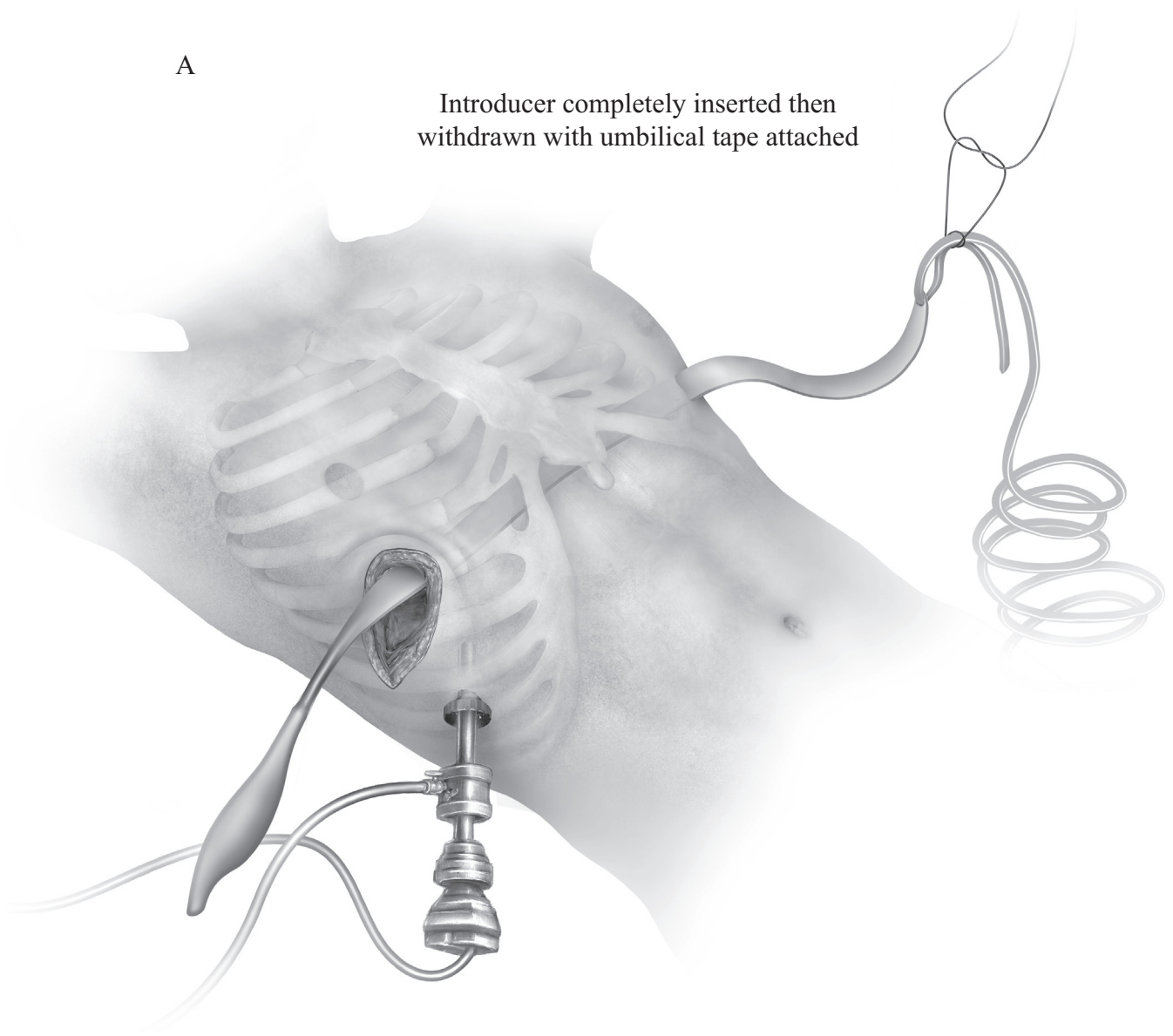
**Figure 9** After the introducer has emerged through the left lateral incision, it will have caused considerable elevation of the anterior chest wall. The mediastinum should be carefully inspected at this time to check that the pericardium is intact, that there is no bleeding, and that there is at least a 1- to 2-cm gap between the pericardium and the anterior chest wall.

It is however necessary to loosen up the chest wall before inserting the bar. Further correction is obtained by lifting the introducer anteriorly on both sides, while the surgeon molds the lower anterior chest wall with his free hand into the desired configuration by pushing down on the lower costal cartilage. The sternum and anterior chest wall are lifted and molded numerous times until the tissue has been stretched sufficiently to take the tension off the introducer. The chest should then be inspected to see if another bar is needed. If the correction is not completely satisfactory, at this point then it is far better to insert another bar at this time, because the repair always looks better when the patient is lying flat on his back (supine) than when standing upright in a normal, slightly kyphotic posture. If a second bar is to be inserted, the first introducer is left in place, until the second introducer is in position. Then the lifting and molding maneuver is repeated with both introducers individually and synchronously.

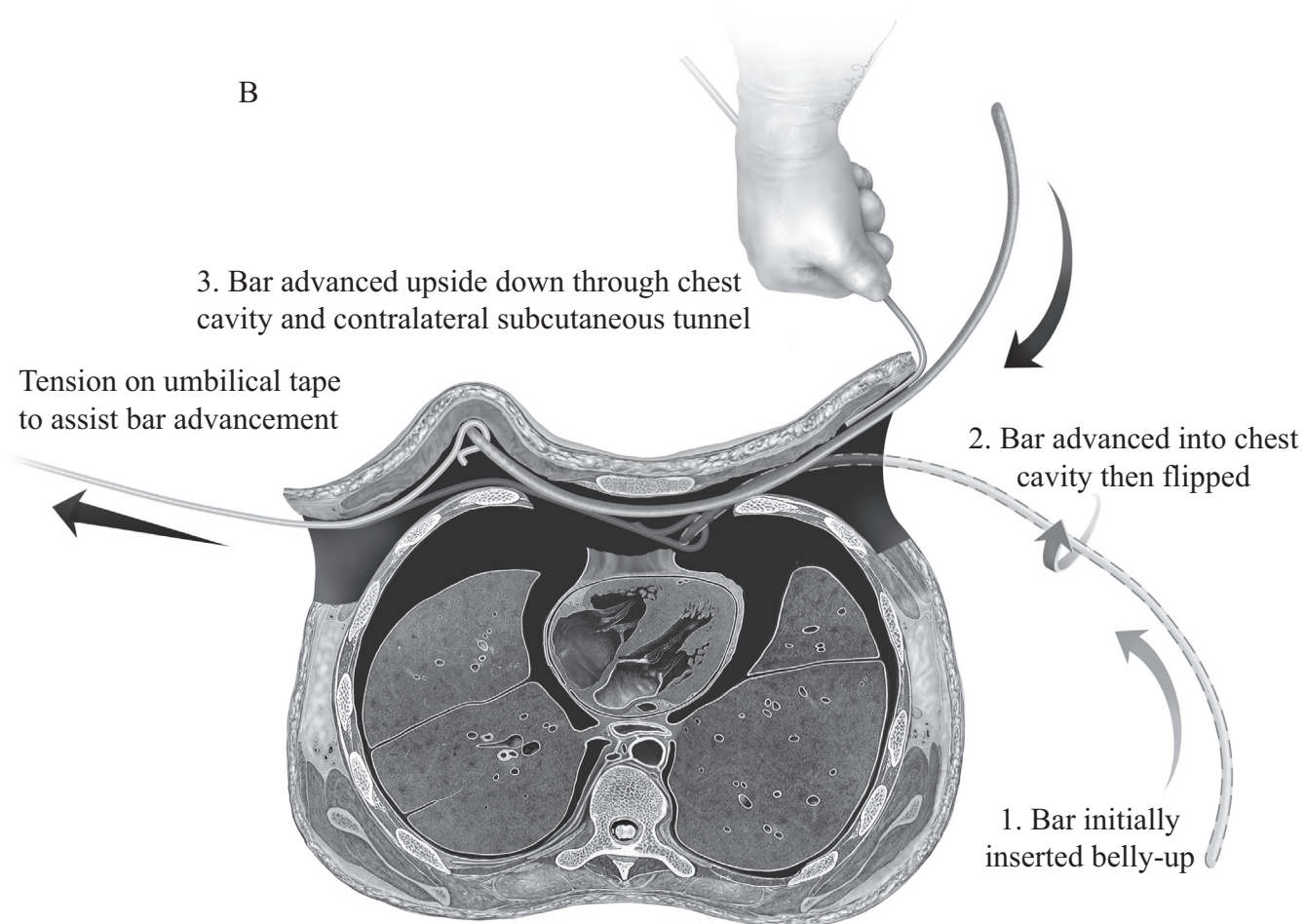
## Inserting the Bar

A

Introducer completely inserted then  
withdrawn with umbilical tape attached

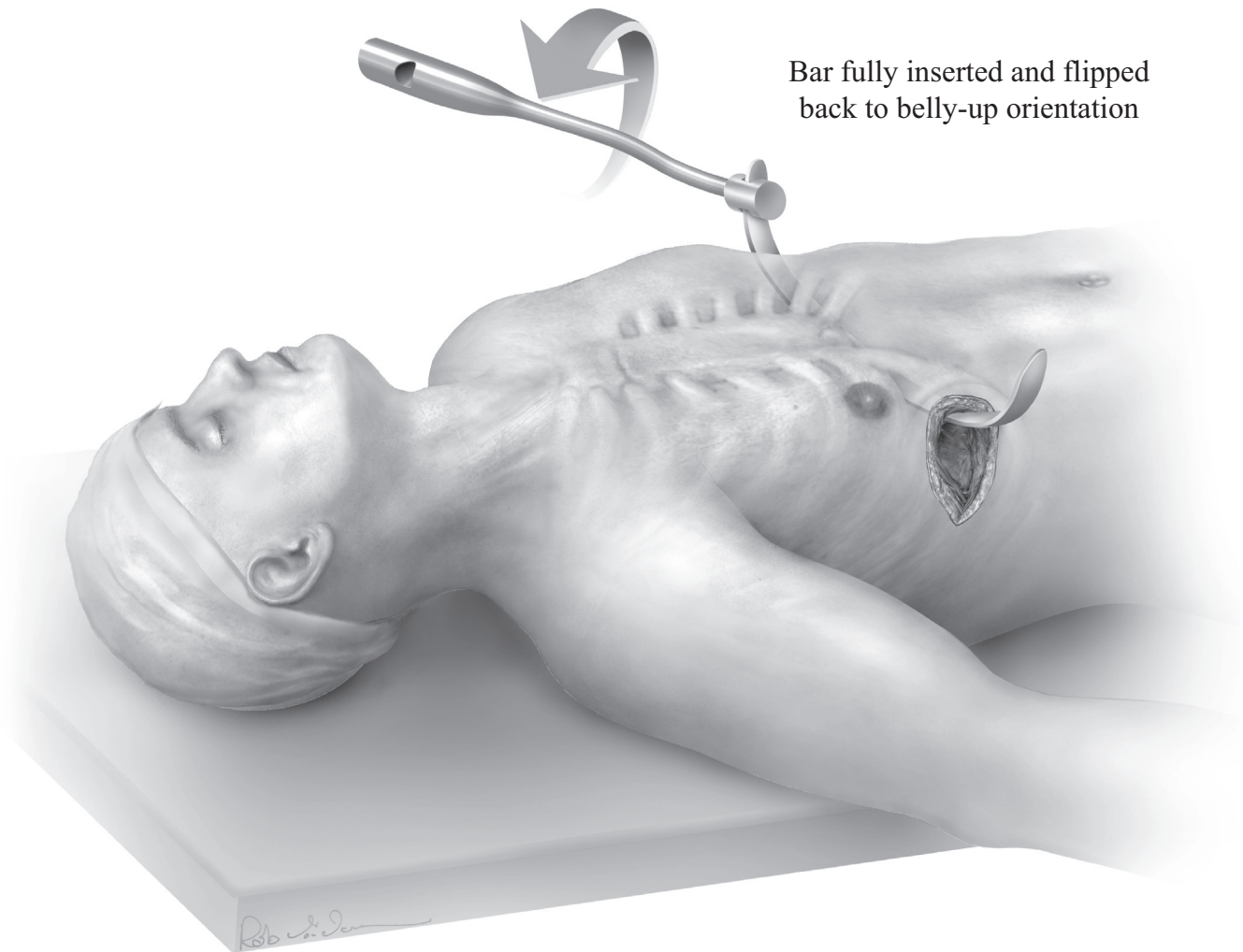


**Figure 10** Umbilical tape is tied to the hole in the end of the introducer, which is slowly withdrawn from the chest under thoracoscopic guidance, thereby pulling the tape through the substernal tunnel. The tape is cut loose from the introducer after exiting the chest on the right. The tape is then tied to the hole in the bar and used to gently pull and guide the bar through the chest by light traction on the tape, once again under strict thoracoscopic control. The bar is inserted into the thoracostomy site with the convexity facing anteriorly, and when it has entered, the chest it is turned over so that the convexity faces posteriorly while it is guided through the mediastinum and out through the thoracostomy on the left. The bar is positioned so that an equal amount of bar protrudes through both incisions.

**Figure 10** (Continued)

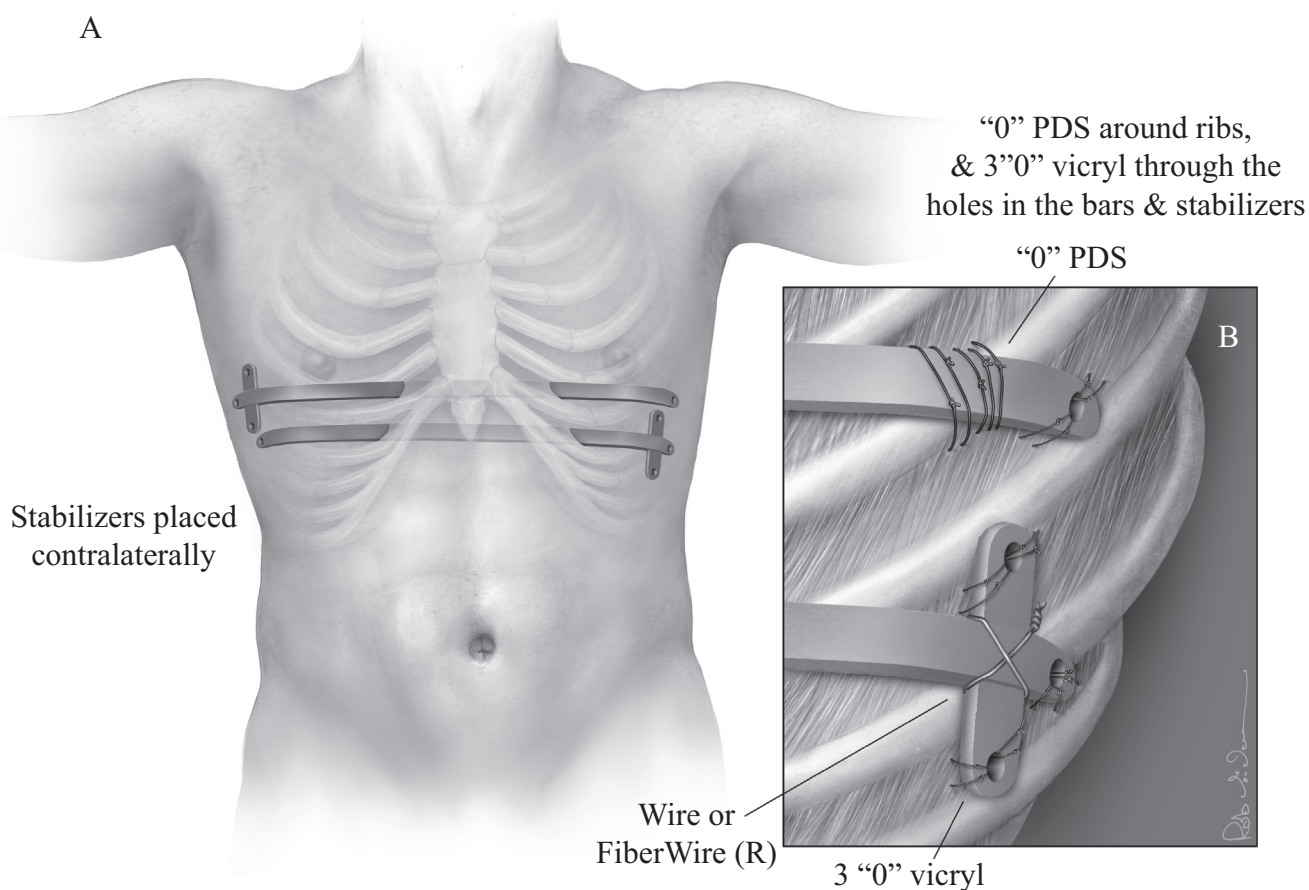


## Turning the Bar



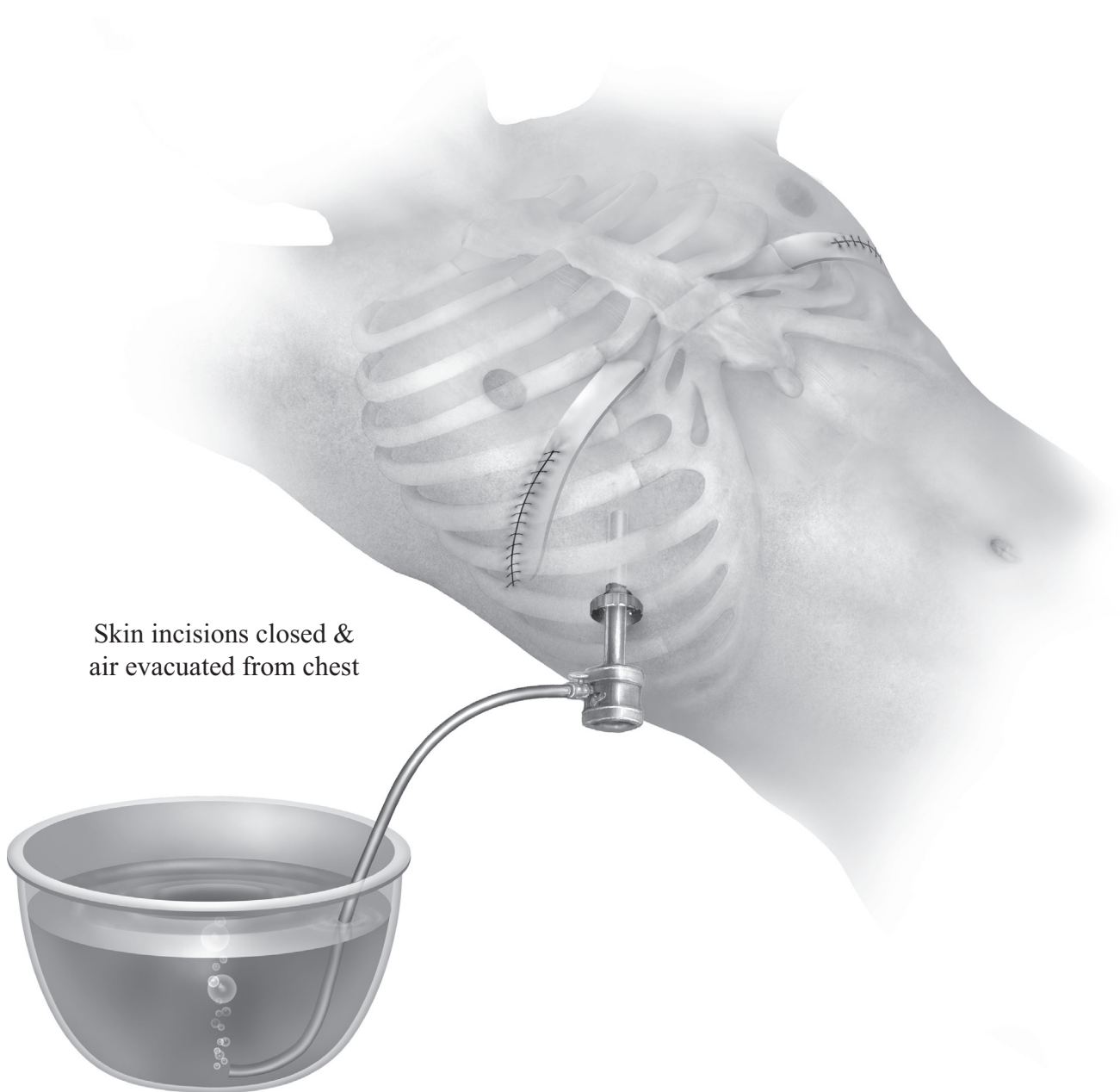
**Figure 11** Bar flippers are attached to each end of the bar which is turned over so that the convexity faces anteriorly. The bar may be turned clockwise or counterclockwise depending on whether the depression is more severe superiorly or inferiorly to the bar. Pressure on the bar after it has been turned over may cause the bar to partially flatten out. In that case, the bar needs to be turned over and either molded in situ with the hand-held bender or removed from the chest with the tape attached, and rebent with the rod bender before being reinserted. When the bar has been successfully turned over it should fit loosely on each side. If it is too tight it will cause rib erosion, pain, and calcification.

## Bar Stabilization

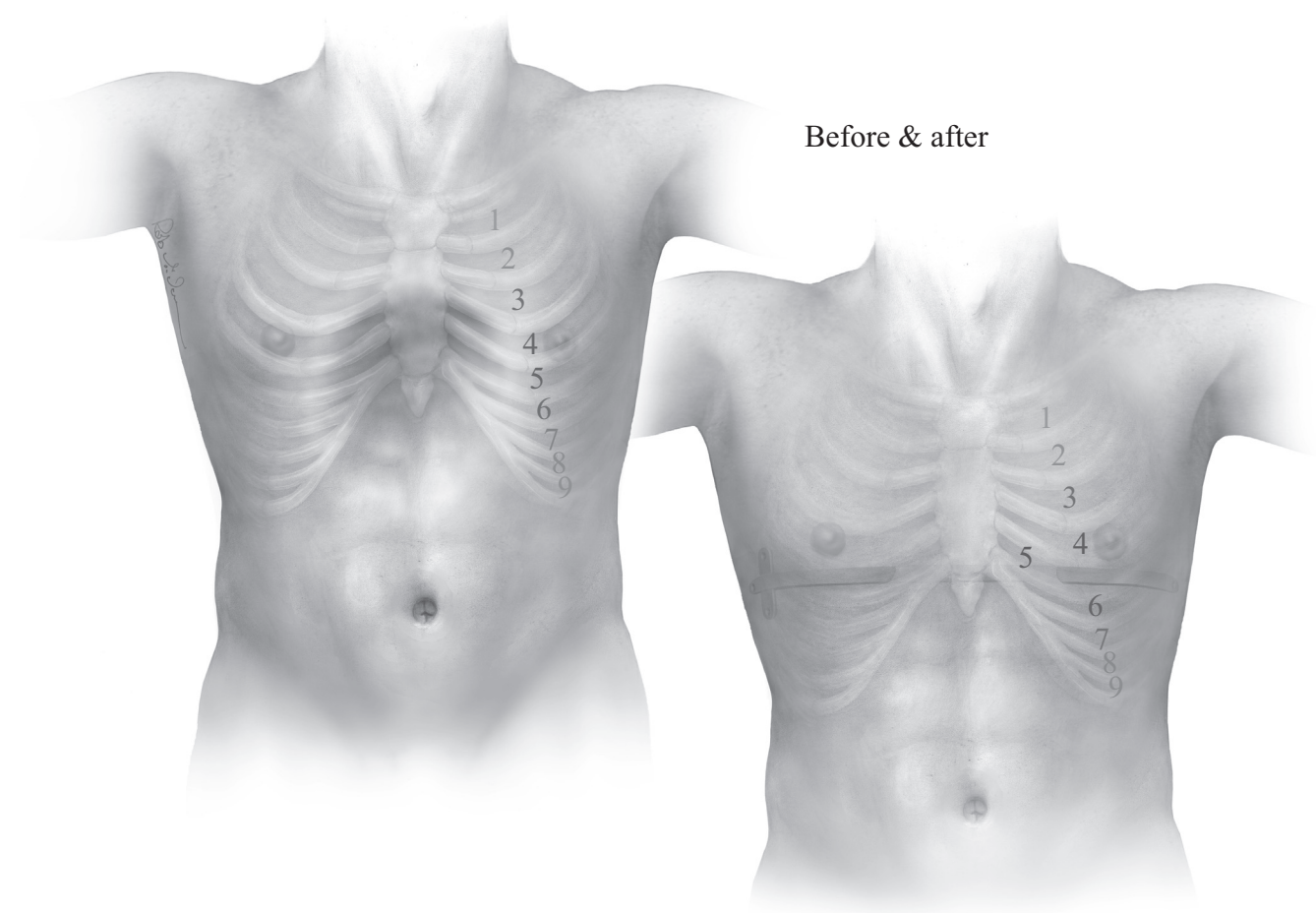


**Figure 12** (A and B) Bar stabilization is absolutely essential. *If the bar is not properly stabilized, it will become displaced and the deformity will recur.* To adequately stabilize the bar, a stabilizer is applied on the left side and attached to the bar with sternal wire or with FiberWire in a figure of 8 fashion. The more medial the stabilizer, the more support it provides. In addition to the stabilizer on the left, multiple "0" PDS ligatures are applied around the bar and underlying rib on the right side. The PDS sutures are placed under thoracoscopic guidance using either a laparoscopic "Endo Close" needle, Doyen suture passer, or a thoracoscopic grasper. The PDS sutures need to be placed exactly at the point where the bar crosses the underlying rib. If the sutures are placed in the wrong site, they will help to displace the bar rather than stabilize it. Sutures should be placed in more than one site, if possible, including the left side. The sutures need to be snug but not tied so tightly that they strangulate the underlying intercostal nerves and blood vessels. PDS = polydioxanone.

## Closure of the Skin Incisions and Evacuation of the Pneumothorax



**Figure 13** Of course, the incisions must be closed before the pneumothorax can be evacuated. When the incisions are closed and before removing the insufflation trocar, a last inspection is carried out with the thoracoscope to ensure that all is well inside the chest. The pneumothorax can be evacuated by cutting the CO<sub>2</sub> insufflation tubing, placing the proximal end under water seal and expanding the lungs with positive pressure ventilation. When no more air bubbles are seen, even when applying lower chest and abdominal pressure, then it is safe to pull the trocar while the anesthesiologist maintains the patient's lungs inflated with positive pressure. The pneumothorax can also be evacuated by leaving a chest tube in place for 1-24 hours. A PA and lateral chest x-ray should be taken before the patient leaves the operating room to determine if there is a significant pneumothorax and to check the position of the bar(s) for future reference. PA = posteroanterior.



**Figure 14** Before and After Minimally Invasive Repair.

## Postoperative Management

Patients must lie and sleep on their back (supine), without lying on the sides, for 6 weeks. Patients should be kept pain free to prevent bar displacement from excessive movement and agitation. Smooth emergence from anesthesia is very important to prevent bar displacement in the recovery room or during the immediate postoperative period. A pain protocol should be instituted before the patient leaves the operating room. We employ narcotic pain medication, nonsteroidal anti-inflammatory medication, and muscle relaxants. We routinely continue antibiotics for 24-48 h to minimize the chance of a bar infection. Patients should also receive anti-nausea medication and a stool softener or mild laxative. Patients should start using an incentive spirometer as soon as they are awake and every hour thereafter. On the first day after surgery, the patient should be assisted and taught how to get out of bed by a physical therapist.

## Long-Term Outcomes

During the first 10 years that the procedure was used, from 1987-1997, few patients were referred by the primary care physicians as they thought that the open surgery in very young patients was too radical. This was also the time when we were going through our learning curve. However, after the publication of the minimally invasive technique in 1998,<sup>17</sup> the number of cases referred increased from 4 per year to more than 100 per year. With the increase in experience, we were able to make modifications that made the procedure safer and more efficient. We discovered that the pectus bar used initially was too soft, the duration the bar was left in situ was too short, and it was frequently insufficiently stabilized. New instruments were created specifically for this procedure, which greatly facilitated the operation. Thoracoscopy and the new sternal elevation techniques have made substernal dissection much safer as visibility has improved. The overall results, which include the early learning experience, are as follows:

Children's Hospital of the King's Daughters (CHKD)  
Pectus Deformities: Incidence and Etiology (1987-2013)

Total Evaluated	3836
Pectus excavatum only	2944
Mixed excavatum or carinatum	185
Carinatum only	611
No chest wall deformity	96

Data collected through December 31, 2013

Minimally Invasive Pectus Excavatum Repair: Clinical Experience as of December 31, 2013

- 3836 Patients have been evaluated
- 1921 Patients have had pectus repair\* (50%)
- 1468 Patients have had bar removal
- 1738 Patients have had primary operations
- 1346 Patients have had primary bar removal
- 131 Patients have had re-do operations:
  - 70 Failed Nuss Procedures

- 59 Failed Ravitch Procedures
- 2 Failed Leonard Procedures<sup>†</sup>

\*There are 11 patients that have had a primary and a secondary surgery.

<sup>†</sup>Prior Leonard Procedures were also prior Ravitch Procedures and are counted only once in the analyses.

Early Postoperative Complications of 1738 Primary Surgical Patients

Pneumothorax requiring chest tube	2.4% (n = 42)
Pleural effusion (requiring drainage)	1.7% (n = 30)
Suture site infection	0.6% (n = 11)
Pericarditis	0.2% (n = 5)
Hemothorax	0.2% (n = 4)
Temporary paralysis	0.1% (n = 2)
Cardiac perforation	0.0% (n = 0)
Death	0.0% (n = 0)

Data collected through December 31, 2013

Late Postoperative Complications in 1738 Primary Surgical Patients

Bar displacements	4.6% (n = 80)
Requiring revision	2.7% (n = 47)
Wound infection	2.4% (n = 41)
Bar allergy	2.2% (n = 39)
Overcorrection	1.8% (n = 31)
Recurrence	1.1% (n = 19)
Hemothorax	0.5% (n = 9)

Postsurgical Results: Primary Repairs

Total number of primary repairs	1738
Total numbers or bar removal	1346
Results	
Excellent result	1197 (88.9%)
Good result	130 (9.6%)
Fair result	7 (0.5%)
Failed	12 (1.0%)

## Conclusions

The minimally invasive repair of pectus excavatum is highly successful when carried out by surgeons in a center dedicated to the management of chest wall malformations.

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